15688

TARDEC

--- TECHNICAL REPORT ---

THE NATION'S LABORATORY FOR ADVANCED AUTOMOTIVE TECHNOLOGY

No.

TARDEC

Precision Bearing Grease Selection Guide

March, 2006

By Dr. In-Sik Rhee

WINNER OF THE 1995 PRESIDENTIAL AWARD FOR QUALITY

U.S. Army Tank-Automotive Research,
Development, and Engineering Center
Detroit Arsenal
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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 10 March 2006	3. REPORT TYPE AND DATES COVERED Final

4. TITLE AND SUBTITLE

Precision Bearing Grease Selection Guide

5. FUNDING NUMBERS

6. AUTHOR(S)

Dr. IN-SIK RHEE

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. ARMY TANK –AUTOMOTIVE RD&E CENTER
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8. PERFORMING ORGANIZATION REPORT NUMBER

TARDEC-

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
HQ DEFENSE LOGISTIC AGENT
Attn: J-339
8725 John J. Kingman Road,
Fort Belvoir, VA 22060-6221.

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution unlimited; approved for public release

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words) The study was initiated to develop a precision bearing grease selection guide. As a part of this study, forty lubricating greases used in precision bearings, including instrument bearings was evaluated in a comprehensive series of laboratory tests in order that their properties can be compared and to identify potential lubricating greases for the replacement of unavailable greases. The duration of this study was three years including laboratory testing and preparation times. This study was accomplished in a joint effort between TARDEC and NRL and the ATM F-34 Tribology Subcommittee. TARDEC and NRL performed all routine tasks necessary to support the study with additional guidance and review was done by the ASTM F-34 Tribology Subcommittee.

14. SUBJECT TERMS
ball bearings, ester oil, instrument and precision bearing lubricants, mineral oil, perfluoropolyether oil, polyalphaolefines, silicone oil, pennzane, thickener, lubricating grease

NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRCT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UNLIMITED

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18

298-102

ACKNOWLEDGEMENTS

This study was a part of DoD Aging Aircraft Replacement Program and supported by Defense Logistic Agent (DLA) and Defense Supply Center Richmond (DSCR). All technical aspect was directed and its contents were reviewed by ASTM F-34 Tribology Subcommittee.

The author whishes to thank to those who provided precision bearing greases for this study.

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INTRODUCTION

The U.S. Department of Defense, as a user of many precision rolling element bearings (PREB) including instrument bearings, has seen a significant increase in the logistics effort required to support the procurement and distribution of these items. In addition, as time has passed, some of the greases used in certain PREB are no longer available or require improved performances due to advanced bearing technology/requirements. This implies that replacement lubricating greases must be found, especially in this era of extending the lifetime of DoD assets, with the consequent and unprojected demand for sources of replacement parts[1].

The purpose of this guide is to report on the testing of, to discuss and compare the properties of, and to provide guidelines for the choice of lubricating greases for PREB. The PREB are, for the purposes of this guide, meant to include bearings of ABEC 5 quality[2] and above. This guide limits its scope to lubricating greases used in PREB. The number of lubricating greases used in PREB increased dramatically from the early 1940s to the mid 1990s. In the beginning of this period, petroleum products were the only widely available base stocks. Later, synthetic base oils became available. They included synthetic hydrocarbons, esters, silicones, multiply alkylated cyclopentanes (MAC, tradename: Pennzane) and fluorinated materials, including perfluorinated ethers and the fluorosilicones. This broad spectrum of lubricant choices has led to the use of a large number of different lubricants in PREB applications.

One of the primary goals of this study was to take a broad spectrum of the lubricating greases used in PREB and do a comprehensive series of tests on them in order that their properties could be compared and, if necessary, potential replacement greases be identified. This study is also meant to be a design guide for choosing lubricating greases for future PREB applications. This guide represents a collective effort of many members of this community who span the spectrum from bearing manufacturers, original equipment manufactures (OEMs), grease manufacturers and suppliers, procurement specialists, and quality assurance representatives (QARs) from DoD and end users both inside and outside DoD.

This guide is a tool to aid in the choice of lubricating grease for precision rolling element bearing applications and applies only to precision bearing greases. The other types of greases such as industrial greases or automotive general purpose greases are not covered by this guide. There are two areas where this guide should have the greatest impact: (*1*) when lubricating grease is being chosen for a new bearing application and (*2*) when grease for a bearing has to be replaced because the original grease specified for the bearing can no longer be obtained. The Report contains a series of tests on a wide variety of greases commonly used in bearing applications to allow comparisons of those properties of the grease that the committee thought to be most important when making a choice of lubricating grease. Each test was performed by the same laboratory. This guide contains a listing of the properties of greases by base oil type, that is, ester, perfluoropolyether (PFPE), polyalphaolefin (PAO), and so forth. This organization is necessary since the operational requirements in a particular bearing application may limit the choice of grease to a particular base oil type and thickener due to its temperature stability, viscosity index or temperature-vapor pressure characteristics, etc. The guide recommends replacement greases for those greases tested that are no longer available. The guide also includes a glossary of terms used in describing/discussing the lubrication of precision and instrument bearings.

II. Characteristics of Precision Bearing Greases

(1) Precision bearing greases contain base oil to which a thickener has been added to prevent oil migration from the lubrication site and various additives to improve its operating performance. Currently, many technical articles often designate types of lubricating greases based on their thickeners. However, the operative properties of precision bearing greases depend on the combination of base oil, thickener and additive formulation. This guide distinguishes lubricating greases by their base oil types.

(2) Cleanliness is critical to bearing life. Even microscopic contamination can determine the wear processes that impact bearing life/performance and result in bearing failure. Clean greases or Ultra-filtered greases that exclude particles above a predetermined size can prevent wear on precision bearings and extend the bearing life[3].

(3) The types of thickener material and its quantity are vitally important to obtain a stable grease structure and its physical properties. The improper ratio of thickener to base oil has a profound impact on grease's consistency stability, mechanical stability, excessive oil separation, and thermal-oxidation stability. These physical and chemical properties of the grease tend to dictate the precision bearing's performance and its life.

(4) Thermal-oxidation stability is generally comprehensively observed in the evaporation loss, dropping point, and oxidation stability tests. Typically, a low evaporation loss and excellent oxidation stability are required for precision bearing greases in order to have a long service life.

(5) Tribological properties are some of the important operational parameters in precision bearing greases. Most precision bearing greases often use anti-wear additives to improve their wear prevention properties. Some precision bearing greases incorporate EP additives to improve a load carrying capacity, but this property may not be required in all precision bearing applications.

(6) A wide operational temperature range is desired for the precision bearing greases. This property should be determined based on dropping point test and low temperature characterization at actual operational temperatures. Further testing in high temperature test rigs should be done to validate bearing-lubricant performance at operational temperatures.

(7) Channeling capability of lubricating grease is a critical property for PREB lubrication. It assesses the tendency of the grease to keep oil inside of the precision bearing. This capability tends to form a channel by working down of lubricating grease in a precision bearing, leaving shoulders of unworked grease which serves as a seal and oil reservoir[4].

(8) Corrosion prevention and good water stability (minimal change in consistency under wet conditions) are also important properties to prevent rust on bearing surfaces and to preserve grease consistency.

(9) Apparent dynamic viscosity tends to indicate the usable temperature range of a lubricating grease for high speed precision bearing applications.

(10) Long grease life is desired in precision bearing applications. Most precision bearings are not re-lubricated during their lifetime. Also, the grease life is also dependent on the operational temperature.

(11) A high level of noise generated from a precision bearing is usually caused by surface defects or damage of the anti-friction components (balls, races), due to the solid or semi-solid particles present in lubricating greases. Quiet greases that are formulated with few very small particles particulates or filtered to remove particulates are typically required for precision bearing applications.

(12) Seal compatibility may vary with each lubricating grease. The type of material used in seals will determine which lubricating greases can be used in a particular PREB. Compatibility issues can be resolved by previous experience with PREB or by the ASTM D 4289 test method with actual seal materials (i.e. careful consideration must be given to assure compatibility between the grease and the bearing seal, shield and/or retainer materials.

(13) The base oils, thickeners, and additives dictate precision bearing grease performances. The properties of many based oils used in the precision bearings can be found in the ASTM F-2161 Guide[5].

III. TEST DETAIL

Forty commercially available greases selected for evaluation in this program are listed in Table 1. This table presents the classification of base oils, thickener types, grease manufacturers, and military specification products evaluated in this program. Most of these greases are currently used in precision bearing applications. Table 2 lists the test protocol for this study and covers the test methods, their test conditions, and the testing laboratories. This test protocol covers the essential requirements identified for precision bearing greases. The performance requirements of these greases are very unique. They are dictated by the performance expectations of precision bearings including high speed, low noise, extended life, and no contamination of surrounding components by the bearing's lubricant system. To increase the reliability of test data, all tests were performed by a DoD laboratory and three independent testing laboratories. Most of tests were performed by U.S. Army Tank–Automotive Research, Development and Engineering Center (TARDEC) and three independent laboratories, and the results were monitored by the Naval Research Laboratory (NRL). This continuity of testing should form a solid basis for comparing the properties of the multitude of lubricating greases tested by avoiding some of the variability introduced when greases are tested by different laboratories using different or even the "same" procedures.

Table1. Classification of Tested Greases

Code	Grease	Base oil	Thickener	Manufacturer	Color	Military Standard
G-1	Aeroshell 14	Mineral	Calcium	Shell	Dark orange	MIL-G-25537
G-2	Isoflex NCA 15	Mineral/PAO/Ester	Calcium Complex	Kluber	Almond	No
G-3	DC-44-M	Silicone	Lithium	Dow Corning	Dark pink	MIL-G-15719A
G-4	DC-33-M	Silicone	Lithium	Dow Corning	Light pink	No
G-5	Unisilkon L50/2.	Silicone	PTFE	Kluber	White	No
G-6	Aeroshell 16	Ester	Clay	Shell	Light brown	MIL-G-25760
G-7	Aeroshell 17	Ester	Clay	Shell	Dark grey	MIL-G-21164
G-8	Kluberquiet BQH 72-102	Ester	Polyurea	Kluber	Tan	No
G-9	Kluberspeed BF 72-22	Ester/PAO	Polyurea	Kluber	Ivory	No
G-10	Kluberspeed BF 42-12	Ester/PAO	Lithium	Kluber	Ivory	No
G-11	Klubersynth BH 72-422	Ester/PFPE	Polyurea	Kluber	Tan	No
G-12	Aeroshell 7	Ester	Clay	Shell	Light brown	MIL-PRF-23827, Type II
G-13	Turmogrease Highspeed L182	Ester/PAO	Lithium special	Lubcon	Beige	No
G-14	Turmogrease Highspeed L252	Ester/PAO	Lithium special	Lubcon	Beige	No
G-15	Rheolube 950	Ester	Lithium complex	Nye	Ivory	No
G-16	Rheolube 716R	Ester	Lithium complex	Nye	Almond	No
G-17	Nyetorr 5100	Ester	Lithium complex	Nye	Clear/almond	No
G-18	Royco 27	Ester	Lithium	Royal	Tan	MIL-PRF-23827
G-19	Stamina RLS 2	PAO	Polyurea	Shell	Tan	No
G-20	Isoflex Topas L 32	PAO	Lithium	Kluber	Cream	No
G-21	Isoflex Topas NB 52	PAO	Barium	Kluber	Off-white	No
G-22	Aeroshell 22	PAO	Clay	Shell	Light brown	MIL-PRF-81322, DoD –G-24508
G-23	Aeroshell 33	PAO/Ester	Lithium Complex	Shell	Green	MIL-PRF-23537, Type I
G-24	SL-065	PAO/Mineral	Lithium Complex	Summit	Light brown	MIL-PRF-10924G
G-25	Rheolube 374B	PAO	Lithium Complex	Nye	Cream	No
G-26	Rheolube 374C	PAO	Lithium Complex	Nye	Cream	No
G-27	Krytox 240AC	PFPE, Branched	PTFE	Dupont	White	MIL-G-27617, Type III

Code	Grease	Base oil	Thickener	Manufacturer	Color	Military Standard
G-28	Krytox 240AB	PFPE, Branched	PTFE	Dupont	White	MIL-G-27617, Type II
G-29	Krytox GPL 225	PFPE, Branched	PTFE	Dupont	White	No
G-30	Klubertemp HM 83-402	PFPE	PTFE	Kluber	White	No
G-31	Nyetorr 5300	PFPE	PTFE	Nye	White	No
G-32	Krytox 283AC	PFPE, Branched	PTFE	Dupont	White	MIL-G-27617,
G-33	Krytox L-32 G	PFPE, Linear	PTFE	Dupont	White	No
G-34	Minapure	Ester	Lithium	Nye	Almond	SAE-AMS-G-81937
G-35	Tribolub-2N	PFPE	PTFE	Aerospace Lubricant	Light yellow	MIL-PRF-83261
G-36	Rheolube 2000	MAC (Pennzane)	Sodium Complex	Nye	Almond	No
G-37	Braycote 600EF	PFPE, Linear	PTFE	Castrol	White	No
G-38	Braycote 601EF	PFPE, Linear	PTFE	Castrol	Almond	No
G-39	Andok C	Mineral	Sodium Complex	ExxonMobil	Dark brown	No longer manufacture.
G-40	Mobil 28	PAO	Clay	ExxonMobil	Red	MIL-PRF-81322, DoD-G-24508

Table 2. TEST PROTOCOL

Test	Method	Test Condition	Testing Laboratory	Evaluation
Dropping Point	ASTM D 2265	Standard	U.S. Army TARDEC	Measure the temperature at which the first drop of grease falls from the cup
Oil Separation (static)	ASTM D 1742	Standard	U.S. Army TARDEC	Measure the oil separation of grease under normal storage conditions
Oil Separation (Dynamic)	ASTM D 4425	40 C, 2hrs	U.S. Army TARDEC	Measure the oil separation of grease by a high speed centrifuge force
Work Penetration	ASTM D 217	Standard	U.S. Army TARDEC	Measure the consistency of the grease. Higher number indicates a soft grease
Copper Corrosion	ASTM D 4048	Standard	U.S. Army TARDEC	Measure corrosion on copper metal in comparison to the ASTM Copper Strip Corrosion Standards. The 1a and 1b ratings indicate no corrosion
Rust Preventive	ASTM D 1743	Standard	U.S. Army TARDEC	Determine the rust preventive properties of greases using grease lubricated tapered roller bearings stored under wet conditions (flash water). No corrosion is pass rating.
Water Stability	ASTM D217	Procedure A	U.S. Army TARDEC	Measure water stability of greases by using a full scale grease worker. The change in consistency after being subjected to water is a measure of the water stability of the grease. Small difference indicates better water stability.

Test	Method	Test Condition	Testing Laboratory	Evaluation
Water Washout	ASTM D1264	Standard	Petro-Luburicants Testing Lab	Measure the percentage weight of grease washed out from a bearing at the test temperature.
Oxidation Stability	ASTM D 5483	Standard	U.S. Army TARDEC	Measure the oxidation induction time of grease under oxygen environments. A longer induction time indicates better oxidation stability.
Evaporation Loss	ASTM D 972	Standard	U.S. Army TARDEC	Measure the evaporation loss of greases at 99 C.
High temperature Evaporation Loss @180 C	ASTM E 1131 (TGA)	1 hr	U.S. Army TARDEC	Measure the evaporation loss of grease at 180 C.
Channeling Ability	ASTM D 4693 (Bearing Test)	Visual check after bearing test	U.S. Army TARDEC	Determine channeling capability of grease in a lubricated tapered roller bearing.
Apparent Dynamic Viscosity	TA Rheometer	At 25 °C	ICI Paints Strongsville Research Center	Measure apparent dynamic viscosity of a grease at 25 C
Wet Shell Roll Stability	ASTM D	Procedure B	U.S. Army TARDEC	Measure water stability of greases using a roll stability test apparatus, small sample required. . The difference in cone penetration before and after being worked in the presence of water is a measure of the effect of water on the grease. Small difference indicates better water stability.
Work Stability	ASTM D 217	Standard	U.S. Army TARDEC	Determine the work stability using a grease worker. The difference between the cone penetration before and after working is a measure of the worked stability of the grease. Small difference indicates better worked stability.
Roll Stability	ASTM D 1831	Standard	U.S. Army TARDEC	Determine the roll stability of grease. The difference between the cone penetration before and after rolling is a measure of the roll stability of the grease. Small difference indicates better roll stability.
Four Ball Wear Test	ASTM D 2266	Standard	U.S. Army TARDEC	Determine the wear preventive characteristics of greases in sliding- steel-on-steel applications. Measure the diameters of wear scars after the test. A small diameter indicates less wear.
Four Ball EP Test	ASTM D 2596	Standard	U.S. Army TARDEC	Determine the load-carrying properties of greases. It measures Load –wear index (LWI). A high LWI number indicates a better load-carrying property.
Grease Life	ASTM D 3527	Standard	U.S. Army TARDEC	Measure grease life at the test temperature.
Low Temperature Torque	ASTM D 4693	Test temperatures, -20 C, -40 C, -54 C	U.S. Army TARDEC	Measure low temperature property of grease. It measures initial torque and running torque at 1 and 5 minutes. A lower number indicates a better low temperature property.
Rolling Bearing Noise	SKF Be-quite	Standard	SKF	Measure noise level using an acoustic instrument. The rakings are : very noisy (GNX)>noisy (GN1)>standard noise (GN2)>quite (GN3)>very quite(GN4)

Test	Method	Test Condition	Testing Laboratory	Evaluation
Dirt Count	FTM 3005	Standard	U.S. Army TARDEC	Measure the cleanness of greases. Zero indicates no dirt contamination.

IV. TEST RESULTS AND DISCUSSIONS

The test results of the 40 precision bearing grease selected are summarized in Tables 3-5. Each grease tested was assigned a code to mask their source to mitigate any potential bias in the testing results. Each grease was tested for dropping point, consistency, water and work stability, oxidation stability, oil separation, evaporation loss, wear, EP properties, corrosion prevention, low temperature characteristics, cleanliness, apparent viscosity, grease noise, and grease life. Compatibility testing with elastomers incorporated into PREB and their environments were not done due to the large number of combinations that would require testing to span the potential mixes of greases and elastomer components that might occur in bearing applications. It is recommended that the user verify grease/elastomer compatibility when needed.

In these tables, some of the data may not agree with those of manufacturers due to the variation of the test methods and their test apparatuses (i.e., noise test). All tests were performed by a government laboratory and three independent laboratories. No grease manufacturers performed any of these tests except for the base oil viscosities of greases.

Mineral oil base greases are, in general, not recommended as precision bearing greases. These greases may exhibit a high evaporation rate and excessive oil separation. Most of these greases also provide a short lubrication life and do not have good oxidation stability. They do not provide a wide temperature operation capability due to their chemical structure. In addition, their base oils vary from lot to lot depending upon the source of the crude oil used as feedstock and upon the exact chemical and physical processes used to refine the feedstock. The main advantage of mineral oils over synthetic oils is cost. In most PREB applications, the cost of the lubricant is usually a very small part of the overall cost of the bearing. Therefore, in most PREB applications, the differential cost of using a mineral oil versus synthetic oil based greases should not be a determining factor in the choice of lubricating greases.

Polyalphaolefins (PAO) based grease is widely available and is currently used in many PREB applications. PAO greases exhibit many of the physical properties that are required for the lubrication of PREB and have a long history of being used successfully in them. They are formulated with PAO oils, various thickeners, and additives. Their base stocks are very similar in chemical structure to paraffinic mineral oils yet have the advantage of being synthesized. Synthetically producing oil gives the manufacturer considerably more control over its chemical composition and thus controls the lot-to-lot variability and allows tailoring of properties to specific needs. Operational temperature ranges of PAO oil based greases are much wider than mineral oil based greases and their use is recommended for many PREB applications. However, some PAO based greases are not initially suited for the precision bearing

applications. For example, they might require filtration processing to remove solid contamination prior to use.

Ester oil based grease is used in several PREB applications. The main advantage is that ester oil based greases have excellent lubricity and compatibility with a wide variety of lubricant additives and have a wide use temperature range. They have somewhat better low-temperature behavior and have a much longer lubrication life than PAO based greases in a high temperature operation. Many of these greases are currently used in PREB applications. Ester oil based greases are incompatible with some sealing materials such as Buna-n and care must be taken in selection of bearing seals when using them.

Silicone oil based greases have not been commonly used in PREB except in moderately high temperature applications where loads are low. They have outstanding oxidation stability at high temperature and exhibit low volatility. Their upper operational temperature usually depends on the stability of the thickener. The rheology of silicone greases is similar to that of the mineral oil based greases. The disadvantage of these greases is its poor lubricity and load carrying capacity. For this reason, the silicone greases normally are not used in ball bearing applications. Also, these greases may have a tendency to creep, possibly contaminating adjacent hardware, and leave fairly hard deposits on bearing parts. This problem may be an issue when considering silicone greases as a PREB lubricant.

Perfluoropolyethers (PFPE) based grease are normally thickened with polytetrafluoroethylene (PTFE). PFPE greases are chemically inert and stable with consistent performance in many conditions. They have high viscosity indexes (about 300), can be used at very low temperatures and have very low volatility. It has marginal lubricity under lightly loaded conditions and may not be acceptable in some of PREB applications. It can be subject to catalytic breakdown under highly loaded (extreme pressure) bearing operation conditions. PFPE greases can be very clean grease when subjected to filtration. They are long life greases in high temperature environments under moderate bearing loads. Currently, PFPE greases are used in many aerospace bearing applications. PEFE greases have a relatively high cost compared to most other synthetic greases. In the past, one problem with PFPE greases was the lack of soluble additives to provide corrosion and anti-wear protection. Today, there are a number of soluble additives available for these greases. However, experience with these additives is limited.

MAC based grease is a special type of grease formulated with a synthetic hydrocarbon based on a multiply alkylated cyclopentane (MAC) oil, sodium complex thickener, and additives. Currently, MAC based greases are used in aerospace applications. It is thermally stable and has low volatility. Its volatility is comparable with PFPE based greases. However, unlike the PFPE lubricants, conventional additives used in PAO and ester oil based greases can also be used in MAC greases to enhance their performance, but these additives can slightly increase the volatility of the grease in high vacuum applications. Because of its low volatility and improved lubricity, MAC based lubricants have replaced PFPE lubricants in several vacuum applications. As with the PFPE based greases, cost is high. Also, availability of MAC lubricants is currently limited due to its sole source supply.

TABLE 3. GREASE TEST DATA (A)

Code	Dropping point (c)	Oil Separation (Dynamic) (%)	Worked Penetration (mm)	Coppe r Corros ion	Rust Preventive	Water Stability (1/10mm)	Wet Shell Roll Stability (1/10 mm)	Work Stability (1/10 mm)	Roll Stability (1/10 mm)	Four ball wear (mm)	Greas e life (hrs)
G-1	151	39	284	1a	Pass	62	53	47	37	0.36	27
G-2	215	24	284	1a	Pass	---	12	---	22	0.56	225
G-3	217	0.5	263	1b	Pass	-11	-8	40	3	2.20	295
G-4	218	3	285	1b	Pass	14	8	16	12	1.24	423
G-5	334	43	268	1b	Pass	---	-3	---	-4	2.27	354
G-6	321	45	295	1a	Pass	132	119	82	76	0.58	394
G-7	263	42	302	1a	Pass	25	37	59	49	0.49	231
G-8	286	5	259	1b	Pass	---	58	---	36	0.36	397
G-9	279	6	252	1a	Pass	---	69	---	45	0.40	300
G-10	338	24	266	1a	Pass	---	55	---	57	0.60	180
G-11	269	0.4	286	1a	Pass	---	21	---	10	0.44	371
G-12	282	45	321	1a	Pass	29	23	36	42	0.54	110
G-13	323	14	290	1b	Pass	---	11	---	4	0.47	90
G-14	279	13	249	1a	Pass	---	18	---	5	0.52	100
G-15	273	25	244	1b	Pass	---	83	---	25	0.49	240
G-16	195	32	318	3a	Pass	---	39	---	18	0.51	210
G-17	203	11	260	1b	Pass	---	113	---	47	0.85	170
G-18	187	34	271	1a	Pass	---	>162	41	24	0.91	100
G-19	213	5	274	1a	Pass	9	1	17	-8	0.48	400
G-20	194	57	257	1b	Pass	---	37	---	20	0.58	171
G-21	279	28	266	1b	Pass	---	7	---	3	0.48	120
G-22	310	47	290	1a	Pass	125	97	37	97	0.69	271
G-23	242	53	297	1a	Pass	7	7	12	10	0.52	140
G-24	256	13	281	1a	Pass	-2	-3	28	26	0.48	201
G-25	227	21	291	1b	Pass	---	38	---	22	0.35	49
G-26	225	8	213	2c	Pass	---	41	---	3	0.40	161
G-27	243	16	266	1b	Pass	---	11	---	19	0.83	397
G-28	191	33	260	1b	Pass	---	38	---	13	0.72	400
G-29	213	29	263	1b	Pass	---	42	---	22	1.00	450
G-30	293	13	275	1b	Pass	---	-4	---	30	0.87	365
G-31	217	31	256	1a	Pass	---	59	---	46	0.68	>500
G-32	221	33	303	1b	Pass	---	17	---	12	0.90	309
G-33	199	35	279	1a	Pass	---	-13	---	8	1.13	>500
G-34	207	19	218	1a	Pass	---	137	---	94	0.77	60
G-35	187	14	307	4a	Pass	---	21	---	34	1.41	>500
G-36	318	24	232	1b	Pass	---	80	---	70	0.37	>500
G-37	239	22	281	1b	Pass	---	10	---	1	0.77	>500

G-38	235	22	290	1b	Pass	---	1	---	6	0.87	>500
G-39	277	2	285	-	Pass	---	---	---	---	0.46	60
G-40	>343	29	317	1a	Pass	-3	-14	1	-15	0.53	261

TABLE 4. GREASE TEST DATA (B)

Code	Oil Separation (Static) (%)	Four Ball EP LWI	Evaporation Loss (%) At 99 °C	Dirt Count Particles per milliliter			Water Wash out (%)	Evaporation Loss at 180 °C, % (TGA)	Low Temperature Torque			
				25-75 microns	75-125 microns	125+ microns			Test temperature °C	Break away (N.m)	1 min (N.m)	5 min (N.m)
G-1	16.5	23	0.88	500	200	100	5.63	41.2	-54	4.93	1.9	1.63
G-2	3.0	53	0.23	650	100	0	1.53	3.6	-40	2.47	1.27	0.93
G-3	0.3	28	0.26	350	100	50	1.46	1.3	-40	2.18	1.4	1.12
G-4	1.4	29	0.46	350	50	0	2.31	1.3	-54	0.86	0.43	0.4
G-5	0.9	22	0.14	50	0	0	1.00	0.4	-40	5.85	1.97	1.64
G-6	0.6	66	0.35	100	0	0	2.67	2.4	-54	3.98	1.83	1.46
G-7	6.1	68	0.60	250	50	0	1.69	5.2	-54	0.82	0.53	0.47
G-8	0.5	25	0.06	100	50	0	2.97	2.6	-40	2.79	1.72	1.59
G-9	0.9	39	0.19	50	0	0	2.16	3.6	-40	0.9	0.43	0.39
G-10	5.3	39	0.20	0	0	0	5.40	2.6	-54	1.92	1.22	1.09
G-11	0.01	38	0.10	0	0	0	0.61	2.3	-20	2.67	1.61	1.41
G-12	2.6	39	0.53	400	0	0	1.47	6.4	-54	0.74	0.52	0.5
G-13	0.0	20	0.26	100	0	0	3.19	2.0	-54	2.34	1.53	1.19
G-14	0.8	20	0.36	0	0	0	2.43	2.5	-54	2.56	1.47	1.16
G-15	10.3	25	0.35	100	0	0	9.64	2.4	-54	7.1	3.29	2.99
G-16	10.8	20	0.22	100	50	0	6.83	2.1	-54	0.95	0.55	0.49
G-17	5.3	26	0.18	100	0	0	5.49	0.2	-54	36.0	3.48	3.2
G-18	17.1	39	0.58	150	50	0	8.68	11.7	-54	0.91	0.47	0.36
G-19	0.01	21	0.31	0	0	0	0.95	2.0	-40	2.67	1.67	1.47
G-20	7.6	25	0.22	0	0	0	1.51	5.0	-54	0.98	0.5	0.43
G-21	0.5	36	0.10	50	0	0	0.30	1.9	-40	1.27	0.71	0.56
G-22	9.9	39	0.14	400	0	0	0.79	1.8	-54	1.46	1.12	1.01
G-23	10.8	57	0.62	300	0	0	1.24	8.5	-54	1.05	0.54	0.45
G-24	2.0	34	2.10	100	0	0	3.18	6.5	-54	3.51	2.54	1.96
G-25	1.6	26	0.17	0	0	0	3.24	1.1	-40	1.73	1.22	0.87
G-26	0.1	21	0.24	0	0	0	1.42	1.1	-40	2.74	1.97	1.58
G-27	1.7	54	0.06	50	0	0	-	0.2	-40	11.0	5.6	4.77
G-28	4.2	38	0.05	0	0	0	-	1.1	-40	3.88	2.29	2.07
G-29	1.8	67	0.05	0	0	0	-	0.3	-40	5.96	3.67	3.54
G-30	0.8	144	0.03	0	0	0	-	0.1	-40	23.6	9.6	7.32
G-31	3.8	58	0.03	100	0	0	-	0.1	-54	0.8	0.54	0.52
G-32	2.5	44	0.02	0	0	0	-	0.2	-40	11.55	5.09	4.37
G-33	3.1	56	0.08	50	0	0	-	1.5	-40	14.15	5.31	4.87
G-34	0.1	26	0.29	100	0	0	-	3.9	-54	1.37	0.78	0.64
G-35	6.1	135	0.45	0	0	0	-	5.2	-54	1.66	0.58	0.5
G-36	0.3	22	0.17	0	0	0	-	1.2	-40	1.33	0.65	0.57
G-37	1.9	62	0.0	50	50	0	-	0.1	-54	0.99	0.59	0.47
G-38	1.2	84	0.05	200	0	0	-	0.1	-54	0.96	0.6	0.53
G-39	-	31	-	0	0	50	-	10.9	-20	1.8	1.25	1.09
G-40	0.8	29	0.28	200	50	50	1.2	3.5	-54	2.6	1.55	1.38

TABLE 5. GREASE TEST DATA (C)

Code	Channeling Ability (Torque Test)	Apparent Dynamic Viscosity Poise, @25C, $25s^{-1}$	Rolling Bearing Noise	Oxidation Stability (PDSC) @180 °C, min	Base Oil Kinematic Viscosity (cSt)	
					40 °C	100 °C
G-1	No	223	noisy	9.3	13.92	2.90
G-2	Yes	580	very noisy	32.0	23	5
G-3	Yes	770	Noisy	N[1]	72	19
G-4	Yes	294	Standard noise	N	74	25
G-5	Yes	359	very noisy	N	108	25
G-6	No	184	very noisy	637.9	31.2	6.0
G-7	No	133	very noisy	937.6	10.3	2.9
G-8	Yes	208	Quiet	2675.4	100	11
G-9	No	250	Noisy	986.4	22	5
G-10	No	450	Standard noise	48.0	24	5
G-11	No	332	noisy	2128.1	420	34
G-12	Yes	154	very noisy	938.7	10.3	2.9
G-13	Yes	500	noisy	15.2	18	4.5
G-14	Yes	485	quiet	15.9	25	6
G-15	No	384	very noisy	53.3	20	4.2
G-16	No	144	standard noise	46.8	22	4.7
G-17	Yes	218	Standard noise	13.0	61	9.7
G-18	No	238	Noisy	112.4	9.1	2.7
G-19	No	168	very noisy	445.1	100	13.7
G-20	No	273	very quiet	28.1	18	4
G-21	No	290	Quiet	43.4	30	6
G-22	No	150	very noisy	522.2	30.5	5.9
G-23	No	129	very noisy	115.7	14.5	3.6
G-24	No	635	very noisy	18.1	28.7	5.5
G-25	Yes	267	Standard noise	34.3	60.7	9.5
G-26	Yes	2100	Standard noise	34.9	60.7	9.5
G-27	No	238	Standard noise	N	240	26
G-28	No	191	Standard noise	N	85	11
G-29	No	206	very noisy	N	160	18
G-30	Yes	103	very noisy	N	400	37
G-31	No	65	Quiet	N		
G-32	Yes	208	very noisy	N	240	26
G-33	No	2250	Noisy	N	32	7
G-34	Yes	980	Standard noise	N	-	-
G-35	Yes	77	Noisy	N	-	-
G-36	No	307	Noisy	54.5	110	15
G-37	Yes	138	very noisy	N	150	45
G-38	No	109	very noisy	N	150	45
G-39	Yes	1940	ND	9.1	93	8.8
G-40	No	143	Very noisy	134.4	29.3	5.8

1. No oxidation

V. CONCLUSIONS

The lubricating greases presented in this guide were commonly used in precision rolling element bearings (PREB). These greases were selected for the testing based on the grease survey obtained from DoD, OEM and grease manufactures and evaluated according to the test protocol that was designed by ASTM F-34 Tribology Subcommittee. This test protocol covered the essential requirements identified for precision bearing greases. The performance requirements of these greases are very unique. They were dictated by the performance expectations of precision bearings including high speed, low noise, extended life, and no contamination of surrounding components by the bearing's lubricant system.

To select or replace greases based on the data and properties information presented in this guide alone could be very risky due to the many other factors unique to any specific application (compatibility and environmental issues, system operating parameters and requirements, life issues, and so forth). It is strongly recommended that each user fully evaluate greases for acceptability in their specific application and under conditions duplicating the system environment as closely as possible. Grease selection should be made only after successful performances in system tests have been demonstrated.

It is also recommend that prior to replacing grease in a PREB that all of the existing grease should be removed from the bearing. Reactions may occur between incompatible greases resulting in severely degraded performance. When users have more than one type of grease in service, maintenance practices must be in place to avoid accidental mixing of greases. In addition, all fluids used specifically to prolong storage life of PREBs (preservatives) should be removed prior to lubricating the bearings. Reactions may occur which would degrade the grease.

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APPENDICES

A. PROPERTIES OF BASE OILS FOR LUBRICATING GREASES

A.1 Lubricating greases are comprised of two basic structural components: base oil and a thickening agent. In the selection of proper lubricating grease for a given operating condition it is necessary to know the characteristics of the base oil. Therefore, the main properties of the base oils that are part of this guide will be discussed. It is also recommended that a review of the material safety data sheet be included in the selection process of a lubricant. This will allow an assessment of the health/handling risks associated with particular grease.

A.2 Mineral Oils

A.2.1 *Use*—Multipurpose lubricant for large rolling element bearings, engines, gears, and so forth. These oils can be blended with polyalphaolefins (PAOs) or esters to improve their lubricity and temperature-viscosity characteristics.
A.2.2 *Structure*—Due to the origin and the treatment of the base stocks, the formulated oils exhibit different chemical compositions and variations in their properties.
A.2.3 *Advantages*:
A.2.3.1 Available in a wide range of viscosity grades.
A.2.3.2 Excellent lubricity.
A.2.3.3 Additives can improve performance (antioxidants, corrosion protection, antiwear and EP properties, and so forth).
A.2.3.4 Most sealing materials are compatible (little swelling or shrinking).
A.2.3.5 Most paints are compatible.
A.2.3.6 Cost-effective.
A.2.4 *Disadvantages*:
A.2.4.1 These oils age and oxidize at temperatures above approximately 100°C and form resins, carbonaceous deposits, and so forth.
A.2.4.2 Viscosity index is lower than that of most synthetic fluids (that is, viscosity changes more rapidly with temperature).
A.2.4.3 Oils normally used in instrument bearings have a relatively lower vapor pressure than mineral oils.
A.2.4.4 Not miscible with silicones and perfluoropolyethers.
A.2.4.5 Usually is not preferred in applications where temperatures lie outside of the range from -30 to 100°C.[1]

A.3 Polyalphaolefins (PAOs)

A.3.1 *Use*—The PAO oils are used to lubricate rolling element bearings in guidance systems, gimbals, gyros, and so forth. PAOs are used as base oils for PREB lubricants, especially for wide temperature and high-speed applications.

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[1]This temperature limit is only a general guideline. Individual mineral oils may perform at temperature limits significantly different from this.

A.3.2 *Structure*—PAOs, that is, synthetic paraffinic fluids, are primarily straight chain, saturated hydrocarbons. The PAOs differ in chain length, the degree of branching and in the position of the branches. A higher degree of saturation of the PAO molecules increases their thermo-oxidative stability.
A.3.3 *Advantages*:
A.3.3.1 Available in a wide range of viscosity grades.
A.3.3.2 High thermal and oxidative stability.
A.3.3.3 Low evaporation rates.
A.3.3.4 Excellent viscosity-temperature behavior.
A.3.3.5 Resistant against hydrolysis.
A.3.3.6 High viscosity grades are compatible with most sealing materials and paints.
A.3.3.7 Fully miscible with mineral oils and esters.
A.3.3.8 A full range of additives is available.
A.3.4 *Disadvantages*:
A.3.4.1 Low viscosity grades may shrink/swell sealing materials.
A.3.4.2 Not miscible with silicones and perfluoropolyethers.
A.3.4.3 More costly than mineral oils.

A.4 Esters

A.4.1 *Use*—These fluids are used for lubrication of PREB. They serve as a base oil for low-temperature and high-speed lubricants.
A.4.2 *Structure*—Diesters are esters usually based on lower molecular weight branched-chain alcohols reacted with C_4 to C_{10} aliphatic acids (usually forming azelates and sebacates). The polyolesters are synthesized from the alcohols trimethyl propane (TMP) or pentaerythritol and C_4 to C_8 acids.
A.4.3 *Advantages*:
A.4.3.1 Excellent low-temperature characteristics.
A.4.3.2 Suitable for high-temperature applications up to 150°C.
A.4.3.3 Excellent lubricity.
A.4.3.4 Able to dissolve a wide concentration range of most additives.
A.4.3.5 Low evaporation rates for some diesters and most polyol esters.
A.4.3.6 High thermal and oxidative stability.
A.4.3.7 Miscible with mineral oils, polyalphaolefins, and polyphenylmethylsilicones.
A.4.4 *Disadvantages*:
A.4.4.1 Only available in low to medium viscosity grades.
A.4.4.2 May shrink/swell some sealing materials such as BUNA-N, NBR, and EPDM elastomers.
A.4.4.3 May interact with paint and other polymeric coatings.
A.4.4.4 Can hydrolyze under humid conditions that may cause corrosion.
A.4.4.5 Not miscible with polydimethylsilicones and perfluoropolyethers.
A.4.4.6 More costly than mineral oils.

A.5 Silicones

A.5.1 *Use*—Silicones are used as lubricants for extremely low temperature (down to -75°C) applications. They may also be used for high temperature (up to 220°C) applications under light loads.
A.5.2 *Structure*—There are three classes:
A.5.2.1 Polydimethylsilicones have a linear chain structure with methyl groups.
A.5.2.2 Polyphenylmethylsilicones (siloxanes) have a linear chain structure with methyl and phenyl groups. Siloxanes with a high ratio of phenyl to methyl groups show a decrease in evaporation and low temperature properties over that exhibited by the polydimethylsilicones. Siloxanes also show an improvement in thermal and oxidative stability and in surface tension properties.
A.5.2.3 Fluorinated silicones have a branched structure based on perfluoroalkyl groups. Fluids having a branched chain structure exhibit better load-carrying capacity.
A.5.3 *Advantages*:
A.5.3.1 Available in a wide viscosity range.
A.5.3.2 Polydimethylsilicones along with the linear perfluoropolyethers exhibit the best viscosity-temperature behavior of all lubricating oils.
A.5.3.3 Excellent low temperature properties.
A.5.3.4 Low evaporation rates.
A.5.3.5 Compatible with almost all plastics and sealing materials with the exception of those based on silicones.
A.5.3.6 Good damping properties.
A.5.4 *Disadvantages*:
A.5.4.1 Low surface tension (high tendency to spread and creep with the exception of the polyphenylmethylsilicones).
A.5.4.2 Very poor lubricity.
A.5.4.3 Can polymerize to glassy materials at elevated temperatures and under medium to heavy loads.
A.5.4.4 Not miscible with mineral oils, polyalphaolefins, esters, and perfluoropolyethers.
A.5.4.5 Difficult to remove by solvents.
A.5.4.6 Can decompose in electrical arcs (electrical contacts) forming abrasive deposits.

A.6 Perfluorolpolyethers (Perfluorinated Alkyl Ethers) (acronyms–PFPE, PFAE)

A.6.1 *Use*—These fluids are used as the base oil for high-temperature and oxygen-resistant lubricants. Both linear and branched-chain perfluoropolyethers are available. The linear PFPEs are primarily used for vacuum and space applications due to their very low vapor pressures or where use at very low temperatures is required.
A.6.2 *Structure*—These materials are long chain polyethers containing fully fluorinated alkyl groups. The fluorocarbon subunits may have a linear or branched-chain structure or a mixture of these two subunits.
A.6.3 *Advantages*:
A.6.3.1 Extraordinary high thermal and oxidative resistance.
A.6.3.2 High resistance to chemical attack.
A.6.3.3 Wide operating temperature range. The operating temperature range depends upon the base oil viscosity and molecular structure (i.e. straight chain or branched).

A.6.3.4 Very low vapor pressure and evaporation rate; The evaporating rate is dependent strictly upon the molecular weight and molecular structure. All products are sold with a wide range of viscosities and therefore molecular weights. PFPEs with a linear structure have significantly lower vapor pressures than their branched-chain counterparts.
A.6.3.5 Medium to excellent viscosity-temperature behavior (linear structure–excellent, branched structure–medium).
A.6.3.6 Compatible with sealing materials, plastics, and paints.
A.6.4 *Disadvantages*:
A.6.4.1 Low surface tension (spreading, creeping).
A.6.4.2 Common lubricant additives are not soluble in these materials. Today, there are number of soluble additives available for these greases, but experience with them is limited.
A.6.4.3 Poor corrosion protection for greases with no corrosion protection additives.
A.6.4.4 Tribo-catalytic breakdown of the oil can occur, especially in steel rolling element bearings under high loads where fresh metal exposed by wear can occur. This catalytic breakdown can also occur when in contact with aluminum, magnesium or titanium alloys.
A.6.4.5 Not miscible with other base stocks: mineral oils, esters, PAOs, silicones, and so forth.
A.6.4.6 High density (approximately 1.9 g/ml). The same volume of grease will require twice the weight.
A.6.4.7 Poor boundary lubrication properties for greases with no anti-wear or extreme pressure additives
A.6.4.8 May cause insulating films at electrical contacts.
A.6.4.9 Can deposit monolayer films of PFPE species that are difficult to remove by solvents. The monolayer films will make bearing surfaces unwettable.
A.6.4.10 High cost, especially for linear PFPEs.

A.7 MAC (Trade name: Pennzane)

A.7.1 *Use*—These fluids are suitable as the base oil for greases used in space applications such as high vacuum/low vapor pressure environment.
A.7.2 *Structure*—This material is a part of the multiply-alkylated cyclopentane family. It contains multiple alky groups on the cyclopentadiene ring.
A.7.3 *Advantages*:
A.7.3.1 Low volatility and low vapor pressure.
A.7.3.2 Good Lubricity.
A.7.3.3 Wide operating temperature range.
A.7.3.4 The viscosity of fluid does not change much with temperature due to the high viscosity index (but not as high as the linear PFPE oils).
A.7.3.5 Compatible with conventional oil additive chemistries...
A.7.3.6 Low infrared absorbance
A.7.3.7 Excellent chemical stability in vacuum environments.
A.7.3.8 High surface tension
A.7.4 *Disadvantages*:
A.7.4.1 Water stability problem.
A.7.4.2 Low load-carrying capacity.

A.7.4.3 Poor oxidation stability.
A.7.4.4 High cost.
A.7.4.5 Marginal low temperature capabilities.

B. PROPERTIES OF THICKENERS FOR LUBRICATING GREASES

B.1 Thickener is the term describing the ingredients added to a base oil in order to thicken it into a grease structure. The two basic types of thickeners are organic and inorganic. Organic thickeners can be either soap based or non-soap based, while inorganic thickeners are non-soap based. Simple soaps are formed with combinations of a fatty acid or ester with an alkali earth metal, reacted with the application of heat, pressure or agitation through a process known as saponification. The fiber structure provided by the metal soap determines the mechanical stability and physical properties of the finished grease. In order to take on enhanced performance characteristics, including higher dropping points, complexing agent (i.e., acetate, azelate, sebacate, etc.) is added to the soap thickener to convert it to a soap salt complex thickener.

B.2 Aluminum Soap

A2.2.1 Source—Aluminum stearates.
A2.2.2 Characteristics:
A2.2.2.1 Clarity and virtual transparency, if made from light colored oils.
A2.2.2.2 Smooth texture.
A2.2.2.3 A substantially anhydrous product.
A2.2.2.4 Insolubility in water.
A2.2.2.5 Upper operation temperature is around 79 °C, although dropping point exceeds 110 °C.
A2.2.2.6 Generates more torque and are more difficult to pump than corresponding products made from other soaps.
A2.2.2.7 Shear stability is poor.
A2.2.2.8 Oxidation stability is excellent.
A2.2.2.9 Rust protection is good.
A2.2.2.10 Incompatible with other types of soap.

B.3 Sodium Soap

A2.3.1 Source—Sodium hydroxide reacts with fats and fatty acids to make sodium soaps.
A2.3.2 Characteristics:
A2.3.2.1 Sensitive to water.
A2.3.2.2 Upper operational temperature is around 121 °C. Although dropping point exceeds 177 °C, its upper operation temperature is limited by oxidation and bleed as well as softening.
A2.3.2.3 Low temperature pumpability and torque are adversely affected by the fibrous texture of the soap.
A2.3.2.4 Shear stability is satisfactory.
A2.3.2.5 Oxidation stability can be improved with additives.
A2.3.2.6 Rust problem due to its poor water resistance.
A2.3.2.7 Thermal stability is good

B.4 Calcium Soap (Hydrated)

A2.4.1 Source—Hydrated lime reacts with fatty acids to make calcium soaps.
A2.4.2 Characteristics:
A2.4.2.1 Smooth and buttery texture.
A2.4.2.2 Poor thermal stability due to the water hydration.
A2.4.2.3 Upper operational temperature is around 79 °C, although dropping point is over 96 °C.
A2.4.2.4 Shear stability is fair.
A2.4.2.5 Oxidation stability is poor.
A2.4.2.6 Water resistance is very good.
A2.4.2.7 Rust protection is poor.

B.5 Calcium Soap (Anhydrous)

A2.5.1 Source—Lime reacts with 12-hydroxystearic acid to make anhydrous calcium soaps.
A2.5.2 Characteristics:
A2.5.2.1 Smooth - a buttery texture.
A2.5.2.2 Upper operational temperature is around 110 °C and its dropping point is around 140 °C.
A2.5.2.3 Water resistance is excellent.
A2.5.2.4 Shear stability is good.
A2.5.2.5 Oxidation resistance is acceptable.
A2.5.2.6 Rust protection is poor.

B.6 Lithium 12-Hydroxystearate Soap

A2.6.1 Source—Lithium 12-hydroxystrearic acid makes lithium soaps.
A2.6.2 Characteristics:
A2.6.2.1 Smooth texture and stable to heating.
A2.6.2.2 Upper operational temperature is around 135 °C and dropping point is in a range from about 177 to 204 °C.
A2.6.2.3 Shear stability is excellent.
A2.6.2.4 Oxidation stability is good.
A2.6.2.5 Water resistance is good.
A2.6.2.6 Rust protection is poor but can be improved by additives.
A2.6.2.7 Widely available.

B.7 Aluminum Complex Soap

A2.7.1 Source—Aluminum stearate and benzoic acid makes aluminum complex soaps.
A2.7.2 Characteristics:
A2.7.2.1 Smooth texture and stable to heating.
A2.7.2.2 Upper operational temperature is around 177 °C and dropping point is over 260 °C.
A2.7.2.3 Shear stability is excellent.
A2.7.2.4 Oxidation stability is good.

A2.7.2.5 Water resistance is good.
A2.7.2.6 Rust protection is poor but can be improved by additives.
A2.7.2.7 Incompatible with other types of thickeners.

B.8 Calcium Complex Soap

A2.8.1 Source—Calcium stearate with salt calcium acetate makes calcium complex soaps.
A2.8.2 Characteristics:
A2.8.2.1 Load-carrying and antiwear properties are excellent.
A2.8.2.2 Upper operational temperature is around 177 °C and dropping point is over 260 °C.
A2.8.2.3 Shear stability is excellent.
A2.8.2.4 Oxidation stability is good.
A2.8.2.5 Water resistance is good.
A2.8.2.6 Rust protection is poor but can be improved by additives.
A2.8.2.7 Products tend to become firm in storage when use a high =thickener -content.

B.9 Lithium Complex Soap

A2.9.1 Source—Lithium 12-hydroxystrearic acid and complexing agent such dibasic acid or dimethyl ester makes lithium complex soaps.
A2.9.2 Characteristics:
A2.9.2.1 Smooth texture and stable to heating.
A2.9.2.2 Upper operational temperature is around 177 °C and dropping point is over 260 °C.
A2.9.2.3 Shear stability is excellent.
A2.9.2.4 Oxidation stability is good.
A2.9.2.5 Water resistance is good.
A2.9.2.6 Rust protection is poor but can be improved by additives.
A2.9.2.7 Bearing performance at high temperatures is very good.

B.10 Polyurea Thickener

A2.10.1 Source—Amines and an isocyanate or a diisocyanate makes polyurea thickener.
A2.10.2 Characteristics:
A2.10.2.1 Thermal stability is excellent.
A2.10.2.2 Upper operational temperature is around 177 °C and dropping point is about 243 °C.
A2.10.2.3 Work stability is poor.
A2.10.2.4 Oxidation stability is excellent.
A2.10.2.5 Water resistance is satisfactory.
A2.10.2.6 Rust protection is poor but can be improved by additives.

B.11 Organo-Clay Thickener

A2.11.1 Source—Natural clays with amines.
A2.11.2 Characteristics:
A2.11.2.1 Smooth texture and stable to heating.
A2.11.2.2 Upper operational temperature is around 177 °C and dropping point is over 260 °C.
A2.11.2.3 Oil separation is low.

A2.11.2.4 Oxidation stability is good.
A2.11.2.5 Water resistance is excellent.
A2.11.2.6 Rust protection is poor but can be improved by additives.
A2.11.2.7 Work stability is good.
A2.11.2.8 Clay particle size can result in roughness in bearing operation (high bearing noise).

B.12 PTFE (polytetrafluorethylene) Thickener

A2.12.1 Source—Polymerization of monomer TFE (tetrafluorethylene).
A2.12.2 Characteristics:
A2.12.2.1 White powder.
A2.12.2.2 Exceptional wide range of thermal applications from -260 to 250 °C.
A2.12.2.3 Virtually universal chemical resistance.
A2.12.2.4 Oxidation stability is excellent
A2.12.2.5 Water resistance is excellent.
A2.12.2.6 Excellent sliding properties.
A2.12.2.7 Non-combustible
A2.12.2.8 Good electric and dielectric properties.
A2.12.2.9 Grease gel stability and oil bleed can be a problem.

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ATTN: DTIC OCC
8725 JOHN J KINGMAN RD
STE 0944
FT BELVOIR VA 22060-6218

ODUSD
ATTN: (L) MRM 1
PETROLEUM STAFF ANALYST
PENTAGON
WASHINGTON DC 20301-8000

US CINCPAC
ATTN: J422 BOX 64020 1
CAMP H M SMITH
HI 96861-4020

DIR DLA
ATTN: J-339 (Kenneth Urtel) 1
8725 JOHN J KINGMAN RD
STE 2533
FT BELVOIR VA 22060-6221

JOAP TSC 1
BLDG 780
NAVAL AIR STA
PENSACOLA FL 32508-5300

CDR
DEFENSE SUPPLY CTR RICHMOND
ATTN: DSCR VEB (Craig Hammond) 1
DSCR VC 1
DSCR JBTB 1
8000 JEFFERSON DAVIS HWY
RICHMOND VA 23297-5678

DIR
DEFENSE ADV FISCH PROJ AGENCY
ATTN: ARPA/ASTO 1
3701 N FAIRFAX DR
ARLINGTON VA 22203-1714

Department of the Army

HQDA
ATTN: DALO TSE 1
DALO SM 1
500 PENTAGON
WASHINGTON DC 20310-0500

SARDA
ATTN: SARD TT 1
PENTAGON
WASHINGTON DC 20310-0103

CDR AMC
ATTN: AMCRD S 1
AMCRD E 1
AMCRD IT 1
AMCEN A 1
AMCLG M 1
AMXLS H 1
5001 EISENHOWER AVE
ALEXANDRIA VA 22333-0001

DIR
ARMY RSCH LAB
ATTN: AMSRL PB P 1
2800 POWDER MILL RD
ADELPHIA MD 20783-1145

CDR ARO
ATTN: AMXRO EN (D MANN) 1
RSCH TRIANGLE PK
NC 27709-2211
CDR ARMY TACOM

PROG EXEC OFFICER
TACTICAL WHEELED VEHICLES
ATTN: SFAE TWV TVSP 1
SFAE TWV FMTV 1
SFAE TWV PLS 1
CDR TACOM
WARREN MI 48397-5000

PROG EXEC OFFICER
ARMAMENTS
ATTN: SFAE AR HIP 1
SFAE AR TMA
PICATINNY ARSENAL
NJ 07806-5000

PROG MGR
UNMANNED GROUND VEH
ATTN: AMCPM UG 1
REDSTONE ARSENAL
AL 35898-8060

VEHICLE PROPULSION DIR
ATTN: AMSRL VP (MS 77 12) 1
NASA LEWIS RSCH CTR
21000 BROOKPARK RD
CLEVELAND OH 44135

CDR AMSAA
ATTN: AMXSY CM 1
AMXSY L 1
APG MD 21005-5071

ATTN: AMSTA IM LMM 1
AMSTA IM LMB 1
AMSTA IM LMT 1
AMSTA TR NAC MS 002 1
AMSTA TR R MS 202 1
AMSTA TR D MS 201A 1
AMSTA TR M 1
AMSTA TR R MS 121 (C RAFFA) 1
AMSTA TR R MS 158 (D HERRERA)1
AMSTA TR R MS 121 (R MUNT) 1
AMSTA TR E MS 203 1
AMSTA TR K 1
AMSTA IM KP 1
AMSTA IM MM 1
AMSTA IM MT 1
AMSTA IM MC 1
AMSTA IM GTL 1
AMSTA CL NG 1
USMC LNO 1
AMCPM LAV 1
AMCPM M113 1
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U.S. ARMY TARDEC
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SFAE ASM H 1
SFAE ASM AB 1
SFAE ASM BV 1
SFAE ASM CV 1
SFAE ASM AG 1
CDR TACOM
WARREN MI 48397-5000
PROG EXEC OFFICER
ARMORED SYS MODERNIZATION
ATTN: SFAE FAS AL 1
SFAE FAS PAL 1
PICATINNY ARSENAL
NJ 07806-5000

CDR APC
ATTN: SATPC L 1
SATPC Q 1
NEW CUMBERLAND PA 17070-5005

CDR ARMY LEA
ATTN: LOEA PL 1
NEW CUMBERLAND PA 17070-5007

CDR ARMY YPG
ATTN: STEYP MT TL M 1
YUMA AZ 85365-9130

US ARMY TACOM

DIR
LOGSA PSCC
ATTN: AMXLS TP P 1
11 HAP ARNOLD BLVD
TOBYHANNA PA 18466-5097

CDR AEC
ATTN: SFIM AEC ECC (T ECCLES) 1
APG MD 21010-5401

CDR AVIA APPL TECH DIR
ATTN: AMSAT R TP (H MORROW) 1
FT EUSTIS VA 23604-5577

CDR ARMY SOLDIER SPT CMD
ATTN: SATNC US (J SIEGEL) 1
SATNC UE 1
NATICK MA 01760-5018

CDR ARMY ARDEC
ATTN: AMSTA AR EDE S 1
PICATINNY ARSENAL
NJ 07808-5000

CDR ARMY INDUSTRIAL ENGRG ACTIVITY
ATTN: AMXIBP 1
ROCK ISLAND IL 61299-6000
CDR ARMY WATERVLIET ARSN
ATTN: SARWY RDD 1
WATERVLIET NY 12189

DIR AMC LOG SPT ACT
ATTN: AMXLS LA 1
REDSTONE ARSENAL
AL 35890-7466

CDR FORSCOM
ATTN: AFLG TRS 1
FT MCPHERSON GA 30330-6000
CDR TRADOC
ATTN: ATCD SL 5 1
INGALLS RD BLDG 163
FT MONROE VA 23651-5194

CDR ARMY ARMOR CTR
ATTN: ATSB CD ML 1
ATS13 TSM T 1
FT KNOX KY 40121-5000

CDR ARMY QM SCHOOL
ATTN: ATSM PWD 1
FT LEE VA 23001-5000

CDR ARMY FIELD ARTY SCH
ATTN: ATSF CD 1
FT SILL OK 73503

CDR ARMY TRANS SCHOOL
ATTN: ATSP CD MS 1
FT EUSTIS VA 23604-5000

CDR ARMY INF SCHOOL

CONSTRUCTION EQUIPMENT TEAM
AMSTA: TR-E-ELE/21 (Ed Rudy) 1
WARREN, MI 48397-5000

CDR ARMY TECOM
ATTN: AMSTE TA R 1
AMSTE TC D 1
AMSTE EQ 1
APG MD 21005-5006

PROJ MGR MOBILE ELEC PWR
ATTN: AMCPM MEP T 1
AMCPM MEP L 1
7798 CISSNA RD STE 200
SPRINGFIELD VA 22150-3199

CDR
ARMY COLD REGION TEST CTR
ATTN: STECR TM 1
STECR LG 1
APO AP 96508-7850

CDR
ARMY BIOMED RSCH DEV LAB
ATTN: SGRD UBZ A 1
FT DETRICK MD 21702-5010

CDR ARMY AVIA CTR
ATTN: ATZQ DOL M 1
FT RUCKER AL 36362-5115

CDR ARMY ENGR SCHOOL
ATTN: ATSE CD 1
FT LEONARD WOOD
MO 65473-5000

CDR 49TH QM GROUP
ATTN: AFFL GC 1
FT LEE VA 23801-5119

CDR
RED RIVER ARMY DEPOT
ATTN: SDSRR M 1
SDSRR Q 1
TEXARKANA TX 75501-5000

ATTN: ATSH CD 1
ATSH AT 1
FT BENNING GA 31905-5000

CDR ARMY ABERDEEN TEST CTR
ATTN: STEAC EN 1
STEAC LI 1
STEAC AE 1
STEAC AA 1
APG MD 21005-5059

CDR ARMY CERL
ATTN: CECER EN 1
P O BOX 9005
CHAMPAIGN IL 61826-9005

DIR 1
AMC FAST PROGRAM
10101 GRIDLEY RD STE 104
FT BELVOIR VA 22060-5818

CDR I CORPS AND FT LEWIS
ATTN: AFZH CSS 1
FT LEWIS WA 98433-5000

CDR ARMY SAFETY CTR
ATTN: CSSC PMG 1
CSSC SPS 1
FT RUCKER AL 36362-5363

PS MAGAZINE DIV
ATTN: AMXLS PS 1
DIR LOGSA
REDSTONE ARSENAL
AL 35898-7466

CDR ARMY ORDN CTR
ATTN: ATSL CD CS 1
APG MD 21005

CDR ARMY SOLDIER SPT CMD
ATTN: SATNC-YM (Dr. Schreuder-Gibson) 1
NATICK, MA 01760-5018

Department of the Navy

OFC CHIEF NAVAL OPER
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2000 NAVY PENTAGON
WASHINGTON DC 20350-2000

CDR
NAVAL SEA SYSTEMS CMD
ATTN: SEA 03M3
2531 JEFFERSON DAVIS HWY 1
ARLINGTON VA 22242-5160

CDR
NAVAL AIR WARFARE CTR
ATTN: CODE PE33 AJD 1
P O BOX 7176
TRENTON NJ 08628-0176

CDR 1

NAVAL PETROLEUM OFFICE 1
8725 JOHN J KINGMAN RD
STE 3719, FORT BELVOIR, VA 22060o

CDR
NAVAL SURFACE WARFARE CTR
ATTN: CODE 63 1
CODE 632 1
CODE 859 1
3A LEGGETT CIRCLE
ANNAPOLIS MD 21402-5067

Department of Navy/U.S. Marine Corps

HQ USMC
ATTN: LPP 1
WASHINGTON DC 20380-0001

PROG MGR COMBAT SER SPT 1
MARINE CORPS SYS CMD
2033 BARNETT AVE STE 315
QUANTICO VA 22134-5080

PROG MGR GROUND WEAPONS 1
MARINE CORPS SYS CMD
2033 BARNETT AVE
QUANTICO VA 22134-5080

PROG MGR ENGR SYS
MARINE CORPS SYS CMD
2033 BARNETT AVE
QUANTICO VA 22134-5080

CDR
MARINE CORPS SYS CMD
ATTN: SSE
2030 BARNETT AVE STE 315
QUANTICO VA 22134-5010

CDR
BLOUNT ISLAND CMD
ATTN: CODE 922/1 1
5880 CHANNEL VIEW BLVD
JACKSONVILLE FL 32226-3404

CDR
MARINE CORPS LOGISTICS BA
ATTN: CODE 837 1
814 RADFORD BLVD
ALBANY GA 31704-1128

CDR 1
FMFPAC G4
BOX 64118
CAMP H M SMITH
HI 96861-4118

CDR

NAVAL RESCH LABORATORY
ATTN: CODE 6176 (R. Mowery) 1
4555 OVERLOOK AVENUE, SW
WASHINGTON, DC 20032

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Department of the Air Force

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WASHINGTON DC 20330-1030

AIR FORCE WRIGHT LAB
1
ATTN: W UPOS 1
WUPOSL
1790 LOOP RD N
WRIGHT PATTERSON AFB
OH 45433-7103

SA ALC/SFT
1014 BILLY MITCHELL BLVD STE 1 1
KELLY AFB TX 78241-5603

SA ALC/LDPG
ATTN: D ELLIOTT
KELLY AFB TX 78241-6439

WR ALC/LVRS
225 OCMULGEE CT 1
ROBINS AFB
GA 31098-1647

AIR FORCE WRIGHT LAB

ATTN: WL/MLSE
2179 12TH ST STE 1
WRIGHT PATTERSON AFB
OH 45433-7718

AIR FORCE MEEP MGMT OFC 1
OL ZC AFMC LSO/LOT PM
201 BISCAYNE DR
BLDG 613 STE 2
ENGLIN AFB FL 32542-5303

Other Federal Agencies

NASA
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ANN ARBOR MI 48105

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FUELS & ENGINE. TESTING 1
BDM-OKLAHOMA, INC
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BARTLESVILLE OK 74003

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800 INDEPENDENCE AVE SW
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